NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY
PENSACOLA, FLORIDA

NOTICES

This interim report was submitted jointly by personnel of the Naval Aerospace Medical Research Laboratory, Pensacola, Florida, and the Radiation Sciences Division, USAF School of Aerospace Medicine, Human Systems Division, AFSC, Brooks Air Force Base, Texas.

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The animals used in this work were handled in accordance with the principles outlined in the *Guide for the Care and Use of Laboratory Animals*, prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animals Resources, National Research Council, DHHS, NIH Publication No. 85-23, 1985; and the Animal Welfare Act of 1986, as amended.

This report has been reviewed and is approved for publication.

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The current safety standards for occupational exposure to radio frequency and microwave exposure do not limit the peak power of microwave pulses. To evaluate whether short-duration (93 ns) high-peak-power microwave pulses can alter behavioral performance, four rhesus monkeys were exposed to peak powers of 7.02-11.30 kW/cm^2 while they performed a vigilance task. The behavior consisted of two components: responding on a variable interval schedule on one lever and to reaction time on a second lever. Correct responding on each lever was signaled by auditory stimuli. Trained monkeys performed the task during exposure to 2.37-GHz microwave pulses delivered concurrently with the auditory signals. The estimated peak whole-body specific absorption rate (SAR) for each pulse was between 582.7 and 937.9 kW/kg (54-87 mJ/kg per pulse). Compared to sham irradiation, significant changes in behavioral performance were not observed.

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SUMMARY

Military personnel may be frequently exposed to low-level microwave radiation from guidance, communications, and weapons systems operating at various frequencies and power densities. Recent development of new systems with very high-peak-power microwave pulses and other unique characteristics has increased concern for the safety of personnel working in and around such microwave environments. Additional information is needed to define microwave levels, identify hazards, and specify safe exposure standards of operation.

Earlier studies have shown that behavioral performance of laboratory animals is a sensitive test for the effects of microwave exposure. The objective of this test series was to determine the effects of high-peak-power microwaves produced by a virtual cathode oscillator (VIRCATOR) on the performance of rhesus monkeys (*Macaca mulatta*). Subjects were repeatedly exposed to high-peak-power microwave pulses inside an anechoic chamber while performing a vigilance task. Short-duration microwave pulses (93-ns duration) were delivered concurrent with auditory signals to which the monkeys were trained to respond. In addition, sham exposures were conducted by shielding the monkeys from the microwave pulses using an aluminum foil barrier.

Compared to sham-exposure sessions, the microwave pulses did not produce statistically significant effects on behavioral performance. During the first few microwave pulses, some orienting was noted in two of the monkeys, but this response habituated rapidly with no lasting effect on performance of the vigilance task. No long-term sequelae were noted at 6 months postexposure.

This experiment did not provide evidence of high-peak-power microwave pulse hazards. Therefore, the whole-body SAR limit of 0.4 W/kg for human exposure to microwave energy remains justified. Nevertheless, we recommend additional research on more subjects at other microwave frequencies and higher power densities.

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INTRODUCTION

Present safety standards (1,2) recommend limiting microwave exposure of humans to 0.4 W/kg for whole-body specific absorption rate (SAR) and 8 W/kg for localized SAR. The standards, however, do not limit the instantaneous peak power of pulsed microwave fields. Thus, microwave fields with high peak powers but low pulse repetition rates may satisfy the currently accepted safe SAR limits. The possibility of adverse health effects from pulsed microwave energy with very high peak power has caused some concern about occupational and military working environments. The most widely studied pulsed microwave-induced bioeffect has been the auditory sensation caused by thermoelastic expansion of brain tissue and a propagating acoustic wave producing stimulation of hair cells in the cochlea (3). The auditory effect requires relatively little peak energy, yet radar and proposed directed energy systems are capable of producing peak powers several orders of magnitude above that required for the effect.

While the auditory effect depends on pulsed microwaves, effects associated with very high-peak-power microwave pulses are unknown. Recent studies have investigated the microwave pulse parameters necessary to produce acoustic mechanical vibrations in brain tissue of several mammalian species (4,5). The concern over adverse health effects stems not from the relatively low power microwave pulses necessary to produce auditory stimulation but from very high peak-power pulses putatively capable of producing intense mechanical vibration in brain tissue. This concern requires further research as new devices with very high-peak-output powers are constantly being developed.

Also, behavioral experiments have given conflicting results in determining whether pulsed waves (PW) can facilitate behavioral effects more effectively than continuous waves (CW). A recent study by Lebovitz (6) found that rats performing on a multicomponent fixed ratio (FR) and timeout (TO) reinforcement schedule were not differentially affected by PW and CW microwaves. In this case, whole-body average SARs of 5.9 and 6.7 W/kg were used for CW and PW exposures, respectively. The peak SAR for the PW exposures was 11.2 kW/kg (authors' estimate). In contrast, Thomas et al. (7) investigated the effect of PW and CW microwaves on rats performing a differential-reinforcement-of-low-rate (DRL) schedule at whole-body average SARs of 0.2-3.6 W/kg and peak SARs of 0.2-3.6 kW/kg (authors' estimate). The rate of appropriately timed responses by rats on this schedule was consistently disrupted by PW microwaves but not by CW microwaves at SARs of 2.5 and 3.6 W/kg. Despite the apparent discrepancies, behavioral change has continued to be a sensitive assay for microwave-induced effects. In particular, operant behavior on time-based schedules of reinforcement has proven very sensitive to microwave exposure (8-10).

A safety standard for exposure to high-peak-power microwave pulses can only be established from an extensive experimental data base. In a previous study (11), we found no significant effects of 1.3-GHz pulsed microwaves on rhesus monkey behavior with a peak SAR in the head of 15.52 W/kg. The study reported here used a VIRCATOR exposure system to achieve a much higher microwave peak SAR (582-938 kW/kg) than that used in our previous study.

METHODS

SUBJECTS

Four juvenile male rhesus monkeys (*Macaca mulatta*), obtained from the Naval Aerospace Medical Research Laboratory (NAMRL) primate breeding program, served as subjects. The mean weight of the subjects during the study was 3.34 kg (± 0.14 kg *SEM*). The subjects were fed a standard primate diet (Wayne Co., 24% protein) daily in sufficient quantities (freely available in their cages) to produce a normal-sized animal for that age. Before training, the animals were fed a reduced amount of the same diet daily until their body mass was reduced by 5% of the previously determined ad libitum weight. During the experiment, the monkeys were maintained near this weight except for periods when they were again free-fed for 5-7 days to establish a new ad libitum weight. This procedure resulted in healthy, well-conditioned animals that worked adequately on food-reinforced tasks. The animals obtained their daily food ration (Noyes Co., 750-mg monkey formula L pellets) while performing the experiment. Their diet during the experiment was supplemented only with fresh fruit. Animals were housed one to a cage where water was always available. Photoperiod was regulated to 12-h light and 12-h dark (0700 on, 1900 off). Home cage temperature was maintained at 20.2-23.5 °C. During the experiments at Kirtland Air Force Base, NM (KAFB), a mobile trailer was modified to serve as a vivarium and was located just outside the microwave exposure facility.

APPARATUS

Microwave Pulse Apparatus

Microwave exposures conducted at the Beam Physics Branch of the Air Force Weapons Laboratory, KAFB, New Mexico, used a VIRCATOR to deliver high-power microwave pulses to a large anechoic chamber (12.2 x 6.1 x 6.1 m). This microwave source (called TEMPO) is an axially extracted VIRCATOR operated with a center frequency at 2.3775 GHz. The VIRCATOR launched microwaves into the anechoic chamber by a custom-designed radial horn antenna (1.21-m diameter). This antenna produced an annular shaped beam, with a null at the center, and radially polarized fields. Measurement of microwave energy in the anechoic chamber was accomplished using an open-ended waveguide (WR-430) terminated with a waveguide-to-coaxial cable adapter. Detected microwave energy was attenuated and applied to a crystal detector (Narda No. 503) and displayed on an oscilloscope (Tektronix No. 7104). Cathode-ray tube (CRT) displays were photographed for later analysis. The VIRCATOR also produced soft x rays, which were measured at the location of the monkey chair with both film-badge photodosimetry and thermoluminescent dosimetry (TLD).

Behavioral

The monkeys were restrained in a Styrofoam chair previously described (10) and were handled by personnel wearing heavy leather gauntlets. The restraint chair was placed inside of a large box (108.3 x 81.5 x 86 cm) constructed of Styrofoam panels (5.08-cm thick). The box served to isolate the monkey from audible noise produced by the VIRCATOR. In addition, a white noise source was placed at floor level next to an opening in the rear of the box and produced a 75-dBA masking sound inside the box at head level in the restraint chair. Windows covered with Plexiglas sheets (0.32-cm thick) were in both the top (25.4 x 30.5 cm) and front (35.6 x 43.2 cm) of the box. These windows provided visual access to the monkey. Each animal was monitored by a television camera (Hitachi FP-7) and a video recorder (Panasonic Model No. AG-6400). The front and back panels of the box were held in place by Velcro tape.

The chair was equipped with two plastic levers (7-cm long, 1.3-cm diameter) mounted vertically and in front of the animal: one to the right and the other to the left. Fiber-optic light switches (Microswitch No. CJWZ-3IIP-B) were actuated when the monkey pulled the levers. The fiber-optic switches were connected to light-emitting diodes and light detectors (Microswitch No. FE7C-FR6M) with 15.2-m lengths of fiber-optic cable. Auditory signals were presented to the monkey using an audio speaker (10.2-cm diameter). The speaker was placed on the bottom of the Styrofoam box. The speaker was mounted in a wooden box and enclosed with fine-mesh copper screen (1.5-mm mesh size). The auditory signals were produced by tone generators and audio amplifiers (BRS/LVE No. AO-201 and No. AA-202). The contingencies for the operant schedule and both data collection and storage were controlled by a microcomputer (Zenith Z-248) and a digital interface (Metrabyte, Dascon-1). Control programs were written in compiled BASIC language (Microsoft Corp. GW-BASIC). The microcomputer system was housed in NAMRL mobile field laboratory No. 1. The mobile laboratory is a climate-controlled vehicle constructed specifically for field studies. This vehicle was parked next to the microwave exposure building at KAFB.

The Styrofoam box containing the monkey chair was placed on top of a stack of Styrofoam blocks with the front surface of the box 2.74 m in front of the radial horn and 1.67 m off the center axis of the horn antenna. At this location, the monkey's head was near the center of the annular microwave beam with the long axis of the monkey's body aligned parallel to the magnetic field vector. A pellet feeder (Foringer 750-mg) was mounted on a wooden stand outside of the Styrofoam box to one side of the anechoic chamber (1.26 m above the monkey's head) and delivered food pellets to the monkey chair through a 2.49-m length of Tygon tubing.

PROCEDURE

Behavioral Training

Four monkeys were trained on a multiple schedule using auditory signals as discriminative stimuli. A schematic of the contingencies of the schedule is shown in Fig. 1. The schedule was divided into 2 main components. In the first component, a 1250-Hz pulsed tone was associated with responses on the right lever during a variable interval (VI) schedule (20-s average, 1-84 s range). In the second component, 985 and 3395-Hz tones were associated with responses on the left lever (choice reaction time component). A response on the left lever during the 985-Hz signal resulted in a food pellet, whereas a response on the left lever during the 3395-Hz signal resulted in a 10-s timeout period and no food pellet. The auditory signals (985 and 3395 Hz) were given in random order for 1-s durations at the end of each variable interval. Behavior sessions were 62-min: three 20-min components with a 1-min extinction period between each component.

Monkeys were first given 8 weeks of training in a sound isolation chamber followed by daily training sessions (5 days/week) for 8 weeks in the Styrofoam isolation box before air transport to KAFB. After arrival, the monkeys required approximately six training sessions to re-establish stable performance. In a repeated-measures experimental design (12), the monkeys were exposed to microwave pulses while performing the task. Two microwave exposure sessions and one sham-exposure session were randomly given on different days.

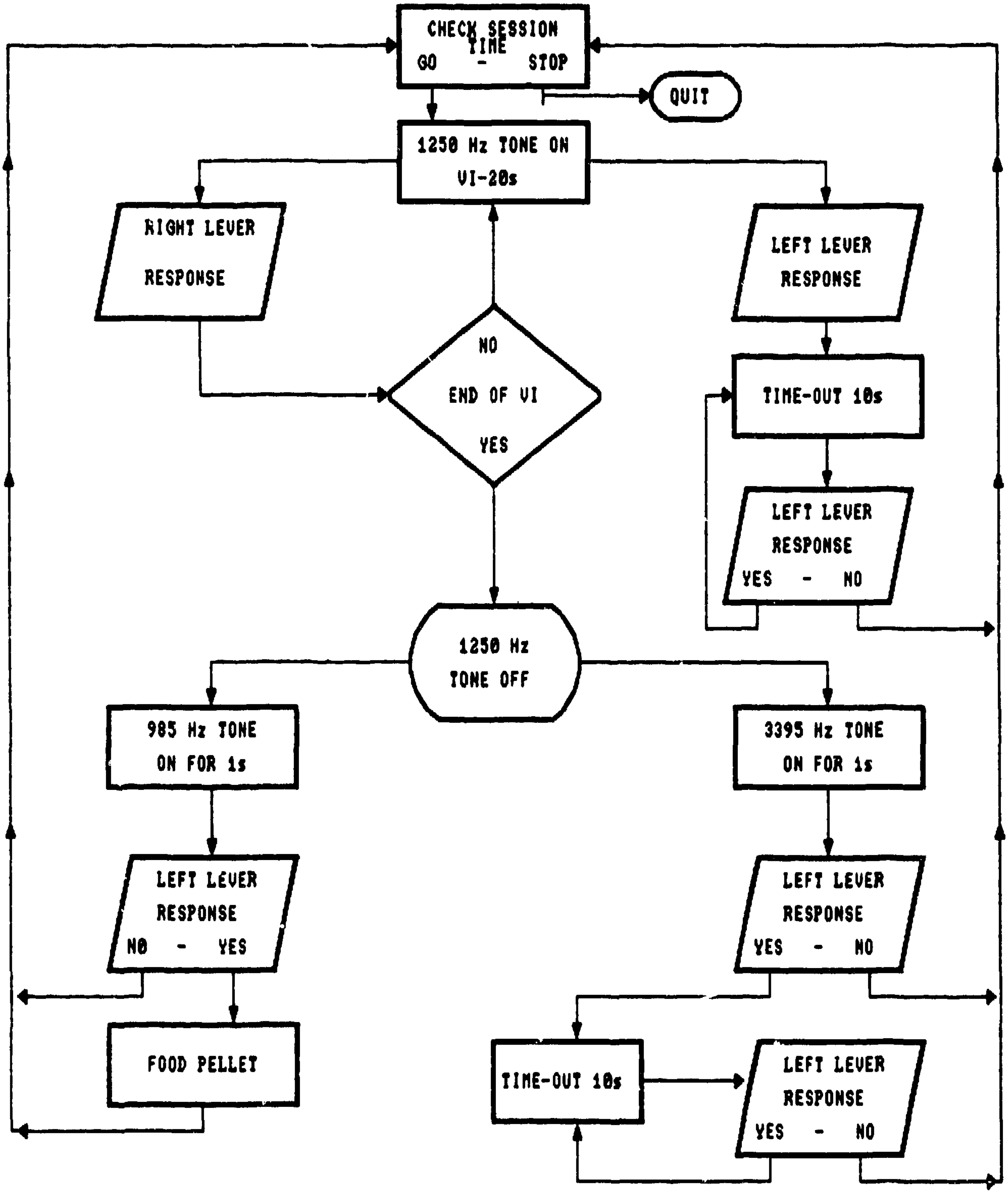

Figure 1. *Schematic diagram of the behavioral task performed by monkeys during microwave and sham exposure.*

Microwave and sham exposures were given during the middle 20-min component of each session with microwave pulses presented during the tone discrimination period (either 985 or 3395 Hz). All training sessions at KAFB, as well as sham and microwave exposure sessions, were videotaped for later analysis. In each experiment, four primary dependent variables were used to evaluate behavioral performance: total right-lever responses, left-lever reaction time, post-reinforcement pause, elapsed time between delivery of a food pellet, and the first right-lever response on the next VI, and post-choice pause elapsed time between a 3375-Hz tone (or white light) and the first right-lever response on the next VI.

Microwave Exposure

Microwave pulses were triggered by the experimenter closing a hand-operated micro-switch. Just before presentation of an auditory signal to the monkey, the experimenter received two signals to deliver a microwave pulse. A visual signal "FIRE" was presented to the experimenter on the microcomputer video monitor, and an auditory beep was produced using the speaker on the microcomputer. Sham exposures were conducted in a similar manner, except microwaves were blocked from the monkey by a Styrofoam sheet (1.2-m diameter, 5.1-cm thick) covered with aluminum foil and inserted into the radial horn antenna. During microwave exposures, the foil was removed from the Styrofoam sheet. Additional details of the exposures are given in Table 1.

TABLE 1. Microwave and Sham Session Summary[a].

Monkey	Number of high-peak-power pulses		
	Microwave sessions		Sham session
	#1	#2	
#64	51	27	36
#24	28	34	42
#57	51	38	32
#32	30	45	34

[a]Center frequency was 2.3775 GHz.
Average pulse duration was 93 ns.
Average peak power density was 8.83 kW/cm^2.
Power density range was 7.02-11.30 kW/cm^2.
Field polarization was H||L.

DOSIMETRY

Local and whole-body SAR could not be measured because of the extremely short-duration VIRCATOR-produced microwave pulses. Consequently, estimates of SAR at 2.3 GHz were obtained using both an analytical model (13) and empirical estimates of monkey models exposed to 2.3-GHz CW microwaves.

Analytical Dosimetry

The predicted whole-body SAR for a sitting rhesus monkey exposed to 2.3-GHz microwaves is 0.083 W/kg per mW/cm^2. This value was obtained from the *Radiofrequency Radiation Dosimetry Handbook* (13) and used with the field power densities measured at the monkey location in the exposure chamber to calculate a whole-body SAR per pulse of 732.9 kW/kg (range = 583-938 kW/kg per pulse).

Empirical Dosimetry

The empirical SAR estimates were obtained by exposing monkey surrogates in an anechoic chamber to CW radiation at 2.37 GHz. An estimate of the local SAR at four body locations was determined using a bag monkey model (5.05 kg), similar to that used by Olsen and Griner (14), filled with simulated muscle tissue (15). A monkey model was mounted in the Styrofoam chair and placed in an anechoic chamber facing a standard gain horn antenna (Narda No. 612). Four small plastic cannulae were inserted in the model from the rear. Two cannulae were placed in the head on the center axis (1 and 3 cm in from the front surface). The head diameter was 7 cm. The third cannula was placed 3 cm from the front surface of the neck, and the fourth cannula was placed 8 cm from the front surface in the chest region. Microwave-compatible temperature probes (Luxtron No. 750) were inserted into each cannula.

Temperature of the model was recorded at 30-s intervals before, during, and after microwave exposure. If the temperature remained stable for several minutes, a 6-min microwave exposure was given using a 1-kW microwave source producing an average power density at the location of the model of 63.0 mW/cm^2, as measured by a field probe (Narda No. 8323). The model was exposed 3 times allowing temperature to stabilize between each exposure. The local SAR was calculated using the following formula: SAR (W/kg) = cT/t, where T is the temperature change in degrees Celsius, c is the specific heat in J/kg/°C and t is the exposure time in seconds. The mean local SAR based on three exposures resulted in the following SARs (normalized to 1 mW/cm^2): head 1-cm 0.21 W/kg; head 3-cm 0.05 W/kg; neck 0.04 W/kg; and chest 0.05 W/kg.

In a similar fashion, an estimate of the whole-body SAR was determined empirically using plastic bottles (3-liter volume, 33-cm length, 13-cm diameter) filled with physiological saline. The bottles were placed in the Styrofoam chair and exposed to microwave radiation for 10 min. The SAR was calculated using the formula given above. The mean normalized SAR based on 4 exposures of the saline-filled plastic bottle was 0.075 W/kg (± 0.006 W/kg *SD*). This value is very close to the 0.083 W/kg from the *Radiofrequency Radiation Dosimetry Handbook* (13).

Ionizing Radiation Dosimetry

The VIRCATOR produces large amounts of soft x rays from which the monkey must be protected by lead shielding. To monitor the effectiveness of the shielding, each monkey was assigned a film badge and TLD for cumulative exposure across all sessions, as well as another film badge and TLD to measure skin-dose x-ray exposure during a single session. The cumulative exposure dosimetry ranges were 280-650 mR for badge and 752 mR-1.69 R for TLD. The ranges for the single session exposures were 110-120 mR for badge and 130-220 mR for TLD. The skin dose of x rays received by the monkeys was well below the recommended safe human occupational exposure level (16).

RESULTS

Repeated-measures analysis of variance and multiple comparisons were used to test for significant effects (12). Compared to sham-exposure sessions, the microwave pulses did not produce statistically significant effects on behavioral performance. During the initial few microwave pulses, some orienting was noted in two of the monkeys, but this response habituated rapidly with no lasting effect on overall performance of the vigilance task.

Total responses emitted during each 20-min session component are shown in Fig. 2. Compared to components 1 (pretest) and 3 (posttest), both microwave exposures, given during component 2 (exposure), did not alter the number of responses emitted by each monkey as compared to the sham exposures ($p > 0.05$). Similarly, reaction time on the left lever (Fig. 3) did not show a significant difference between microwave and sham exposure ($p > 0.05$). Likewise, post-reinforcement pause (Fig. 4) was not altered by the high-peak-power microwave pulses as compared to the sham exposures ($p > 0.05$). Finally, post-choice pause (Fig. 5) did not significantly differentiate the microwave exposures from the sham exposure.

DISCUSSION

The results of the experiments suggest that exposure to short high-peak-power microwave pulses with very large peak SARs but low whole-body average SARs did not significantly alter a well-trained behavior. The exposures were well below the average whole-body SAR threshold (4 W/kg) known to disrupt behavioral performance (1). The use of high-peak-power pulses in these experiments did not suggest that the threshold was lower than 4 W/kg. While two of the monkeys exhibited some observable orienting to the microwave pulses, it is not possible to determine whether audible noise produced by the pulse was responsible for the effect. Nevertheless, no lasting effects could be observed on overall performance of the task. Finally, no long-term sequelae were noted up to 6 months postexposure. The microwave pulse parameters used in this study, however, are only a small sample of the many possible parameters that need to be examined before meaningful extrapolation of the animal results to human performance effects and hazards can be done.

This experiment did not provide evidence of high-peak-power microwave pulse hazards. Therefore, the whole-body SAR limit of 0.4 W/kg for human exposure to microwave energy remains justified. Nevertheless, we recommend additional research on more subjects at other microwave frequencies and higher power densities.

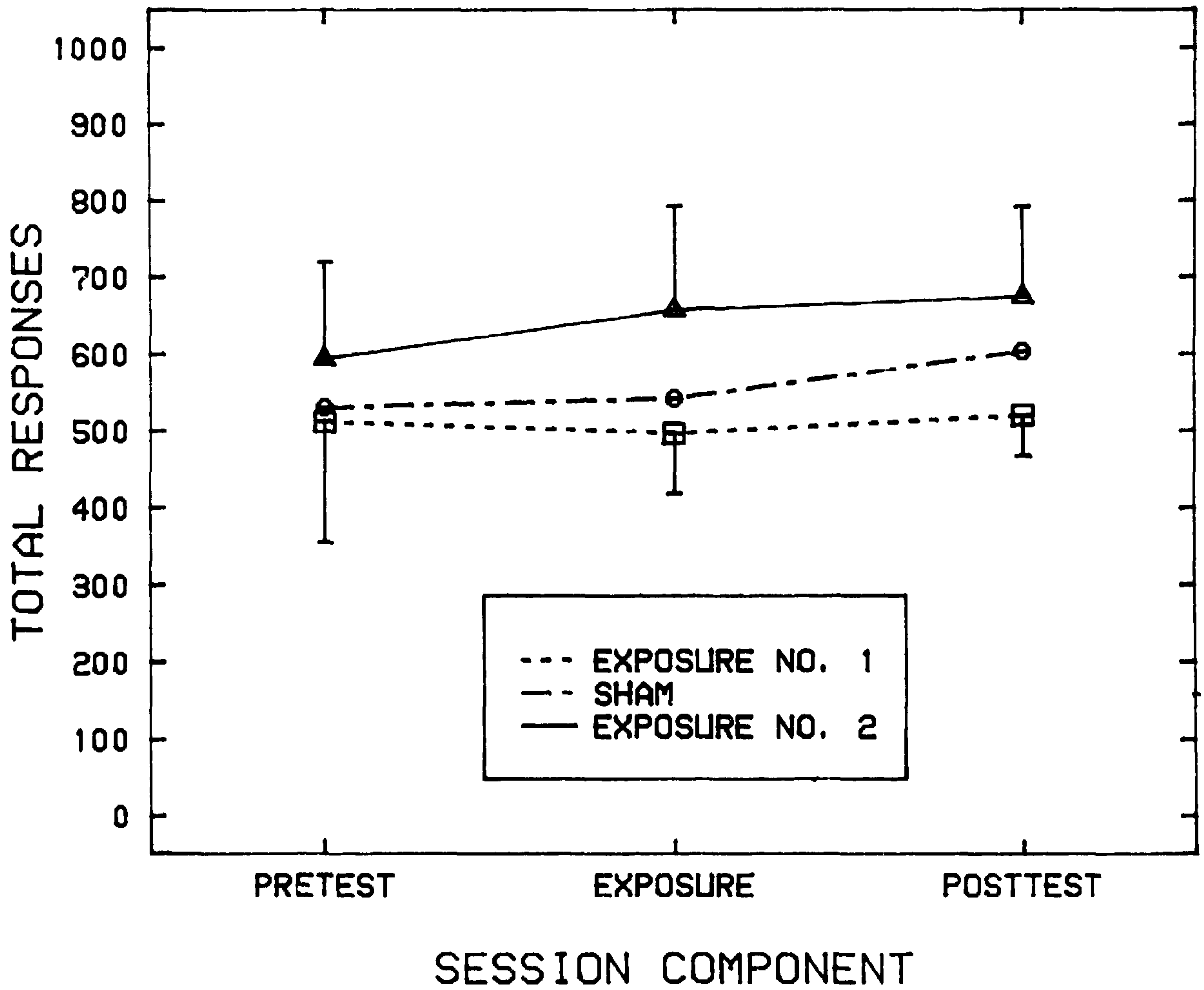

Figure 2. *Mean total responses emitted during each session component during exposures to microwave pulses and sham exposures.*

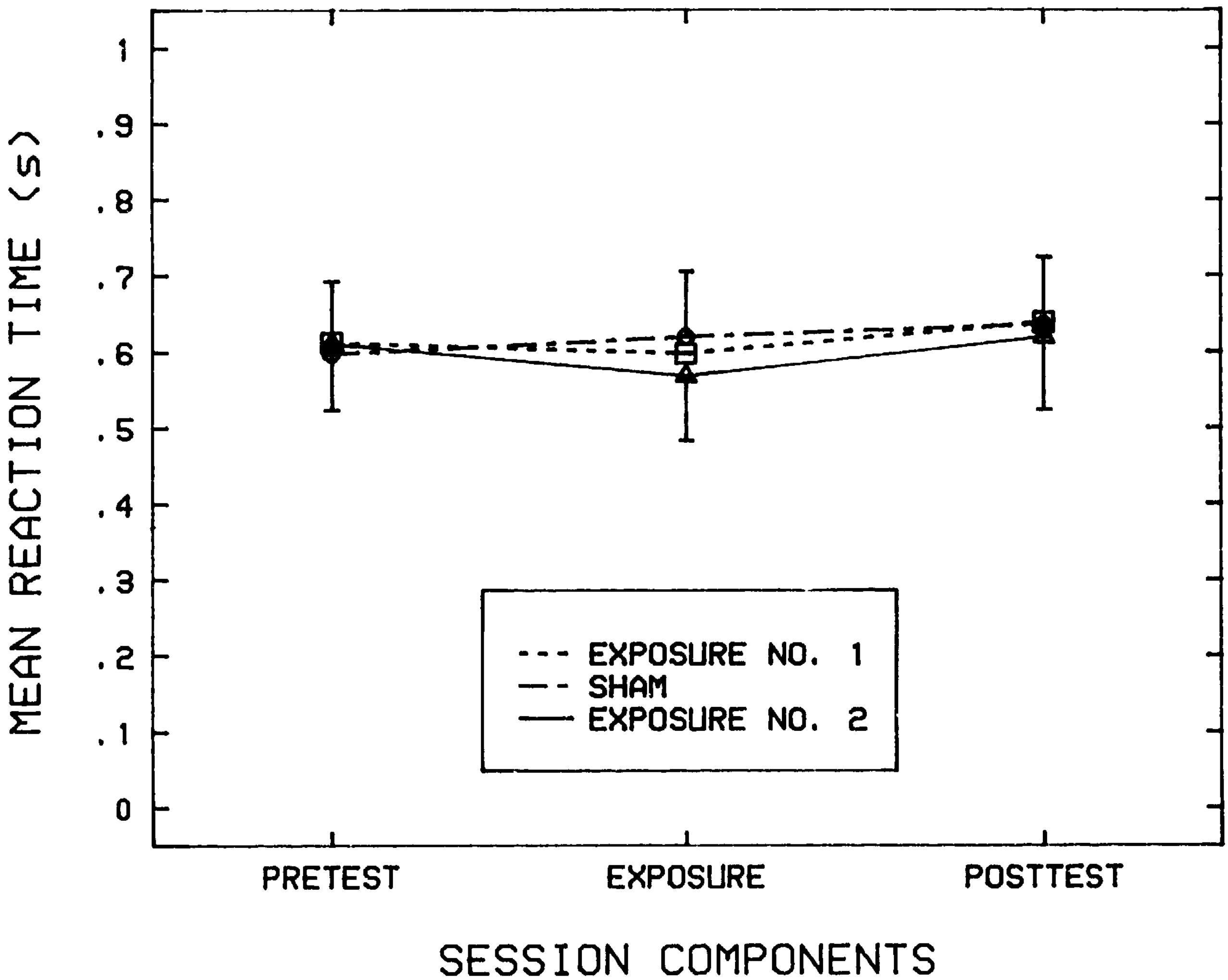

Figure 3. *Mean reaction time (± SEM) following presentation of the 985-Hz tones during each session component.*

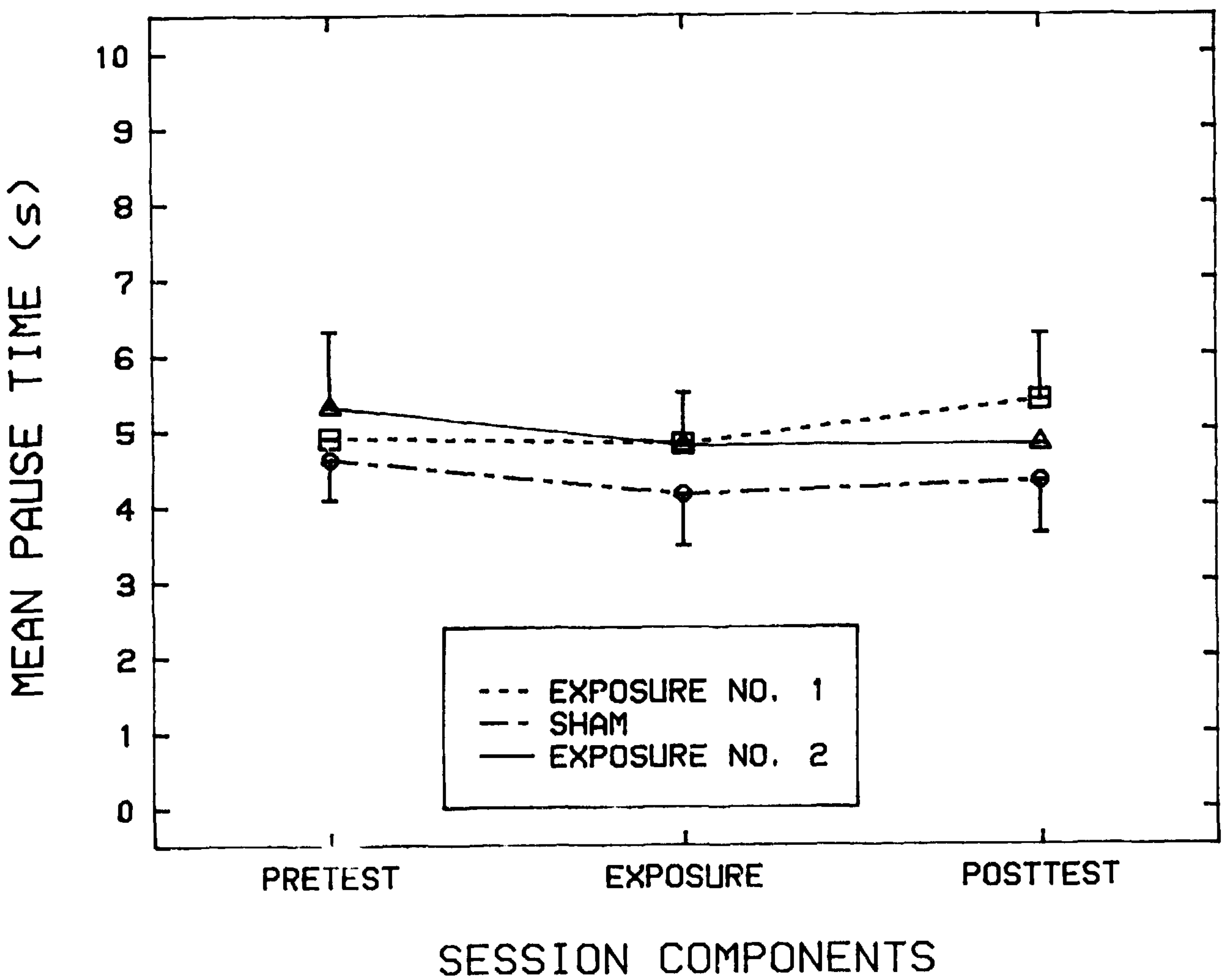

Figure 4. *Mean postreinforcement pause time (± SEM) measured during each session component during exposures to microwave pulses and sham exposures.*

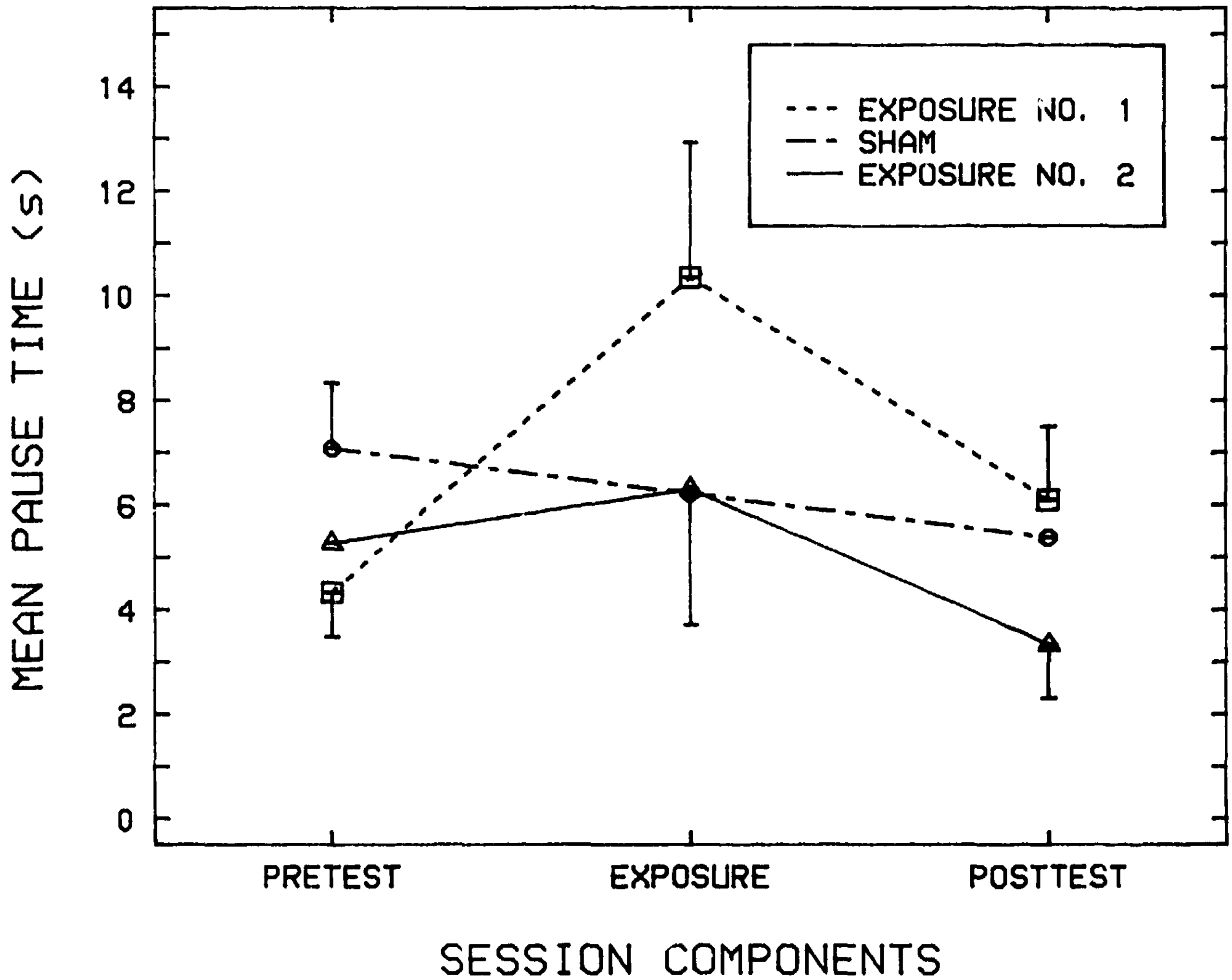

Figure 5. *Mean post-choice pause time (± SEM) measured during each session component during exposures to microwave pulses and sham exposures.*

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